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Ground Shaking in San Francisco

by

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Many of the districts in San Francisco that were strongly damaged in the great San Francisco earthquake of 1906 were also damaged in the 1989 Loma Prieta earthquake. These districts are repeatedly damaged because they are built on soft ground that amplifies the shaking in earthquakes. Structures built on harder ground, such as bedrock, suffer less damage. These differences in the ground type, or surface geology, will affect the shaking in future large earthquakes expected in the Bay Area. Consequently, if you live in an area that shook strongly in the 1989 earthquake or that shakes noticeably in small earthquakes, you can expect strong shaking in future large earthquakes.

This poster presents a simplified geologic map superimposed on a (unrectified) 1982 aerial photograph of San Francisco to indicate how shaking will vary across the city. The geologic map of San Francisco contains many different rock types, which we have simplified into four broad groups: bay mud (including some artificial fill), miscellaneous sands, serpentinite, and the Franciscan assemblage (mostly sandstone). The bay mud is situated around the edge of San Francisco Bay and in the old marshes and stream channels. The sands cover most of the rest of the city, particularly the Richmond, Sunset, and Ingleside Districts. The hills are generally bedrock of either the Franciscan assemblage or serpentinite.

Many factors influence shaking in an earthquake, including the size and proximity of the earthquake source, the directivity or focusing of the wave energy, and the amplification of shaking by the surface geology. The amplification of shaking by the surface geology is the most predictable of these factors. However, the amplification associated with unconsolidated sediments (bay mud and sands) generally increases with their thickness, or the depth to bedrock (not shown). Sites on thin (less than 4 m) layers of either bay mud or sand over bedrock behave as though they were on bedrock. Thus, the amplification is minimal near the sediment boundaries with bedrock, which are mapped to an accuracy of about 30 m (~1 mm on the poster). Note: the simplified geology shown on the photograph is useful only for predicting the relative shaking hazard; other geologic hazards of earthquakes, such as liquefaction (the flow of sand layers) or landslides are not shown.

Engineers who design buildings must consider both the strength of the ground shaking and the frequency at which this shaking occurs. Buildings respond strongly to shaking at particular frequencies. (Frequency is the number of cycles per second; 1 Hz equals one cycle per second.) Earthquakes radiate energy through wave motion, and their waves typically contain a range of frequencies. Engineers and seismologists use a method called spectral analysis to consider the frequency content of earthquake shaking. Spectral analysis transforms time histories to spectra that show the distribution of energy arranged by frequency. The relative amplification of two different sites can be estimated from the spectral ratio — that is, the ratio of the spectra obtained from the two sites during the same earthquake. Generally, a single bedrock site is chosen for the denominator of these spectral ratios, because bedrock does not strongly amplify shaking. For our study, we chose a site at Fort Mason located on Franciscan sandstone. The relative amplifications are plotted on a logarithmic scale on which, for example, the distance between 0.3 and 1.0 is the same as the distance between 3 and 10.

Each of the four broad geologic groups in San Francisco has a characteristic response to earthquakes, and so the spectral ratios for a given rock type are similar to each other, regardless of location in the city. For example, the spectral ratios for bay mud sites in the Marina District resemble the spectral ratios for bay mud sites south of Market Street. The graphs below show the average of the ratios obtained for the sites on each rock type: there were 10 sites on bay mud, 8 sites on sand, only 2 sites on serpentinite, and 8 sites on Franciscan rocks. The width of the colored bands indicates the range of the ratios for each set of sites. The sites on bay mud have the strongest amplification, reaching a factor of 6 at low frequency, but decreasing as the frequency increases. In contrast, shaking at the sand sites is amplified by a factor of 2.5 for frequencies higher than 1 Hz. Shaking at the serpentinite sites is slightly amplified at low frequencies and attenuated at high frequencies. Shaking at sites on Franciscan rocks is not amplified relative to Fort Mason, as expected.

The most important factor controlling earthquake damage to buildings is the construction type: mobile homes and unreinforced masonry structures are relatively weak, while most wood-frame houses that are bolted to their foundations, and steel-frame or reinforced-concrete structures are relatively strong. A building's height, shape, and construction type determine the frequencies of ground shaking that can damage the building. The graphs below show the range of frequencies that can damage typical 2-, 4-, and 10-story buildings. Bay mud strongly amplifies frequencies that can damage 4- and 10-story buildings, rather than 2-story buildings. The damage to the Marina District in the 1989 earthquake illustrates this difference: 4-story buildings were more heavily damaged than smaller structures. Large buildings in the financial district were also at risk, but most of these structures are designed to withstand strong shaking and many are anchored to bedrock. Sands amplify frequencies that can damage 2- and 4-story buildings, but this amplification is less than for 4-story buildings on bay mud. Buildings in the Richmond, Sunset, and Ingleside Districts, which are mostly 2- to 4-stories built on sand, suffered scattered damage in the 1989 earthquake. A stronger earthquake could cause more extensive damage to these neighborhoods.

Cartographic Production by Allan Cartography, Medford, Oregon.

The primary sources of technical material for this map are contained in the following publications.

Bonilla, M.G., 1971, Preliminary geologic map of San Francisco South quadrangle and part of the Hunters Point quadrangle, California: U.S. Geological Survey Miscellaneous Field Studies Map MF-311,1:24,000.

Schlocker, J., 1974, Geology of the San Francisco North quadrangle, California: U.S. Geological Survey Professional Paper 782, 109 p.

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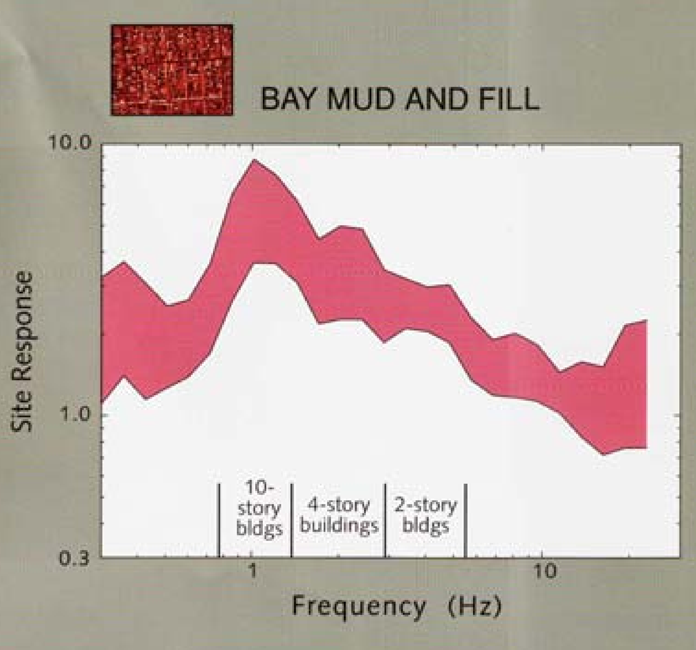

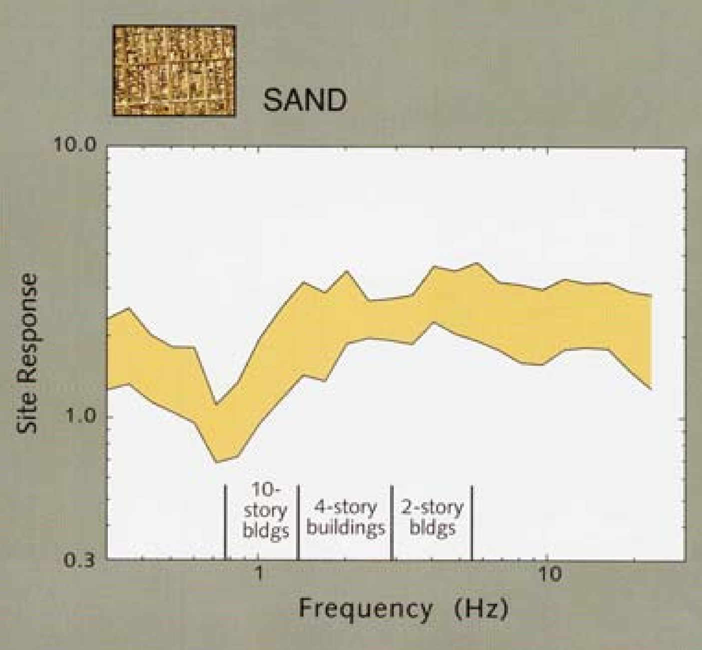

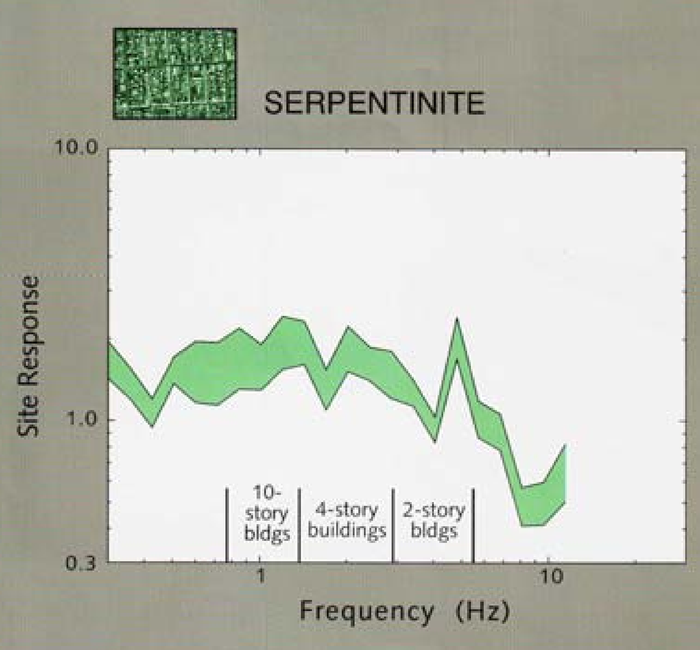

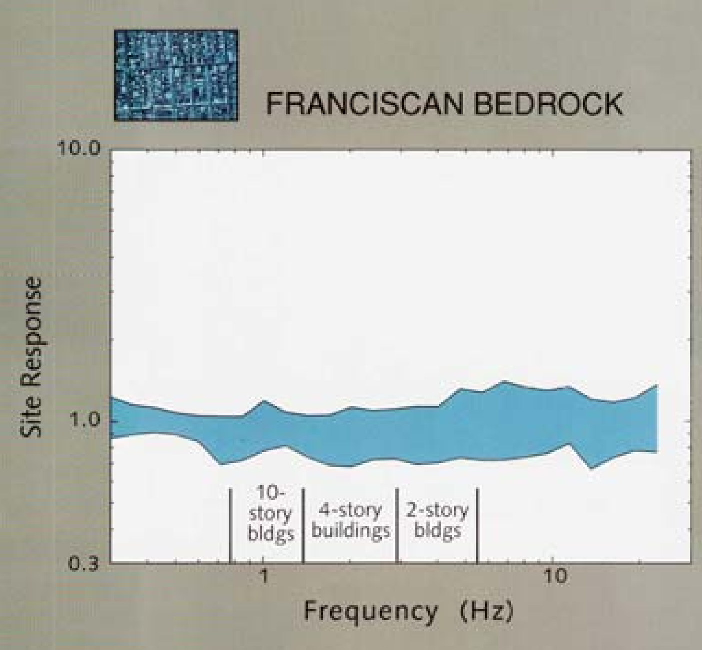

Relative shaking hazard to buildings of varying heights on different rock types

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